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Technological trends in electric topologies for offshore wind power plants

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ABSTRACT

The current situation of the offshore wind market is characterized, among other things, by two opposing forces. On the one hand, there are a few already tested solutions that can be considered almost industrialized under certain conditions of sea bed depth and distance from shore, and investors interested in the offshore wind business will generally demand to keep risks at a minimum. On the other hand, as in any other emerging industry, optimized solutions are far from being available and OWPPs that will be built during the next decade will probably have to introduce new concepts to cope with the new challenges. Industry and academia are proposing alternative topologies for the electric systems of those future power plants, and different solutions are trying to demonstrate their techno-economical leadership in this budding market. The aim of the paper is to analyse the most promising proposals published by researchers and manufacturers during the last few years.

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1. Introduction

Electrical layouts for offshore wind farm (OWFs) were classified by Lundberg [1] into the following six wind farm categories: small AC, large AC, AC/DC, small DC, large DC and series DC wind farms. This classification continues to be very useful, as it takes in most of the topologies proposed during the last decade by the research community. Only recent proposals in relation to multi-terminal high voltage direct current (HVDC) transmission systems are outside the scope of this classification (Sections 3.2 and 4.3).

In the *small AC wind farm* (Fig. 1(a)), the medium voltage alternating current (MVAC) collector system is used both for connecting all turbines in a cluster together and to transmit the generated power to the grid interface point (IP). This IP, also known

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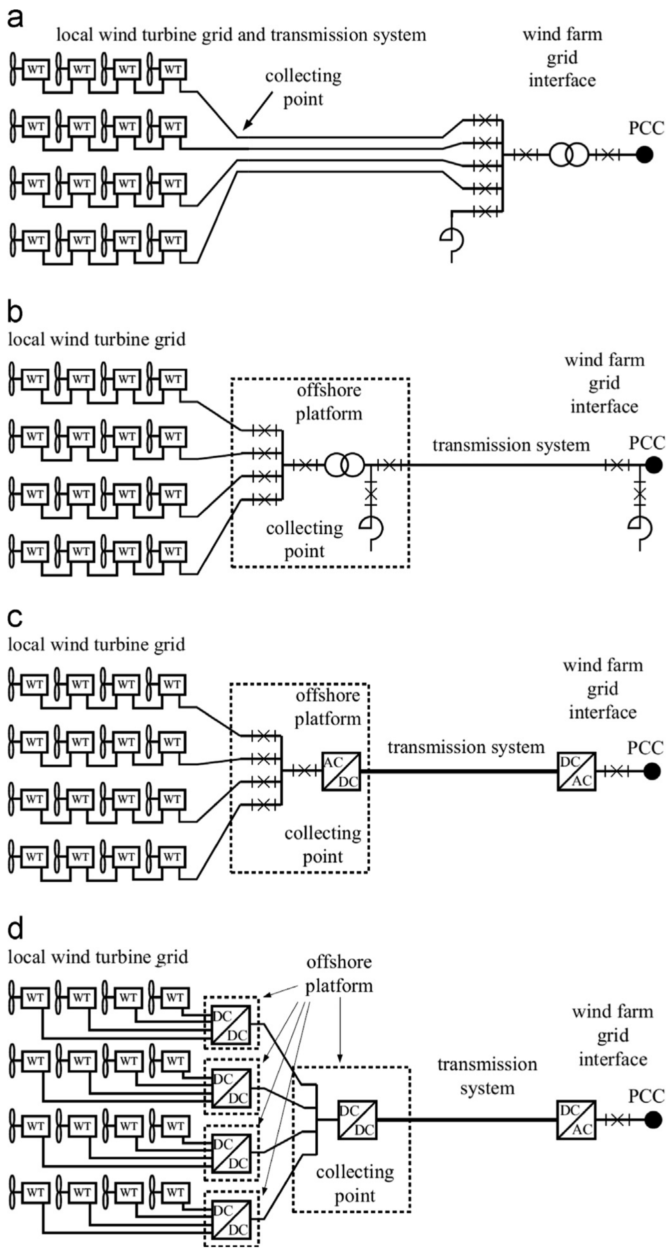

Fig. 1. General layouts for OWPPs between 60 and 300 MW [1]. (a) Small AC wind farm. (b) large AC wind farm, (c) AC/DC wind farm and (d) large DC wind farm with two transformation steps.

as point of common coupling (PCC), is usually placed at the onshore connection point substation (CPS). The main advantage of this layout is that it does not require an offshore substation (OS).

In the *large AC wind farm* (Fig. 1(b)), turbines are clustered within the MVAC collector system. Then, the collector system (CS) is connected to a high voltage alternating current (HVAC) transmission system through an OS in which the transformer, switch gear and auxiliary services are placed.

The layout of an *AC/DC wind farm* is very similar to the previous one, except for the transmission system (TS) (Fig. 1(c)). In this case a HVDC link connects the OWF with the onshore grid and, therefore, the OS, submarine high voltage cables and the CPS will install HVDC technology.

In the *small DC wind farm* each wind energy conversion system (WECS) needs a rectifier to provide its output in DC. The transformer in the wind farm grid interface is replaced with a DC/DC transformer and an inverter. This DC transformation step could be unnecessary depending on the medium voltage direct current (MVDC) output of the turbines. The *large DC wind farm* layout is conceptually similar to that of the large AC wind farm (Fig. 1(d)). The main difference is that one or two voltage transformation steps may be necessary among the offshore wind turbines (OWTs) and the transmission system (TS). In the *series DC wind farm*, the WECSs are connected in series in order to obtain a voltage suitable for the transmission without an OS.

An update of the analysis presented in [2] shows that attending to the installed capacity about 85% of already commissioned OWFs have a large AC layout, whereas about 15% of them have a small AC layout. At the moment there is no operating OWF with an AC/DC layout although there are several HVDC links under construction for offshore wind power plants (OWPPs). Pure DC alternatives should be considered as long term proposals.

With these layouts in mind, the rest of the paper is organized as follows. Section 2 focuses on WECS topologies presented by manufacturers, power converters in these turbines and long-term proposals such as WECS for *fixed-speed* operation and turbines with a DC output. Section 3 presents the evolution of the typical MVAC collector systems and comments on proposals in relation to MVAC collector systems based on multi-terminal voltage source converter (VSC) and MVDC collector systems. Section 4 deals with transmission systems presenting a review of HVAC and HVDC point-to-point links, as well as multi-terminal VSC-HVDC schemes currently under study. Finally, Section 5 summarizes the paper and points out the key aspects of the review.

2. Wind energy conversion systems (WECSs)

The first criteria to classify WECSs in the past was the speed variability, leading to a classification in fixed-speed and variable-speed turbines. Considering the OWTs present in manufacturers' portfolio and a number of recent proposals, all these WECSs follow variable-speed schemes, most of them with full-power converters (Sections 2.1 and 2.2). However, long-term research is also focusing on proposals such as OWTs for *fixed-speed* operation and WECS with a DC output (Section 2.3).

2.1. WECSs for variable-speed operation

The main challenge offshore wind turbines have to face with when compared to their onshore equivalents is the significantly higher operational expenditures (OPEX) mainly due to maintenance associated costs, which may represent around 20% of the total project cost [3]. In order to minimize this drawback the main issues under consideration in new WECSs for offshore wind turbines are the generator type, the stages of the gearbox and the rated power of the electronic converter.

The types of WECSs installed offshore have been the same as those set up onshore, but adapted to the marine environment. The generators in these turbines are doubly fed induction generators (DFIGs), with partial-power converters connected to the rotor through slip rings, permanent magnet synchronous generators (PMSGs) and squirrel cage induction generators (SCIGs) with full-power converters.

Considering the installed capacity operating by the end of last year, about 58% of commissioned OWTs is based on SCIGs, about 40% of them is based on DFIGs and a residual 2% is based on PMSGa. However, the situation is quite different in which concerns attending to the new turbine prototypes and concepts unveiled during the last two years [4–8]. Table 1 presents a survey of the characteristics of the WECSs present in most of the turbines in the 4.0 MW–10.0 MW range. It can be pointed out that about half of these WECSs are based on direct drive (DD) schemes with PMSGs,

Table 1
General characteristics of WECSs in new offshore wind turbines.

Company	Model turbine	Full-scale prototype	Power (MW)	Diameter (m)	Generator		
					Type[a]	Voltage	Gearbox[b]
Areva	M5000	2004	5.0	116/135	PMSG	MV	2
Repower	5M	2004	5.0	126	DFIG	LV	3
Bard	Bard 5.0	2008	5.0	122	DFIG	LV	3
Repower	6M	2009	6.2	126	DFIG	LV	3
Bard	Bard 6.5	2011	6.5	120	PMSG	LV[c]	3
Siemens	SWT-6.0-120	2011	6.0	120/154	PMSG	LV	0
Sinovel	SL 6000	2011	6.0	128	DFIG	–	3
XEMC-Darwind	XE/DD	2011	5.0	115	PMSG	–	0
GE Energy	4.1-113	2011	4.1	113	PMSG	–	0
Guodian UP	UP-6000	2012	6.0	128	DFIG	–	3
Alstom Power	Haliade 150	2012	6.0	150	PMSG	–	0
CSIC Haizhuang	CSIC H127	2012	5.0	127/154	PMSG	–	3
Siemens	SWT-4.0-130	2012	4.0	130	SCIG	LV	3
Daewoo SME	DSME 7.0	2013	7.0	160	PMSG	–	2
Mitsubishi PSE	SeaAngel	2013	7.0	165	PMSG	MV	0[d]
Nordex	N150/6000	2013	6.0	150	PMSG	MV	0
Ming Yang WPIG	SCD 6.0	2013	6.0	140	PMSG	–	0
2B-Energy	2B6[e]	2013	6.0	130	DFIG	–	3
AMSC-Hyundai HI	HQ5500	2013	5.5	140	PMSG	MV[f]	0
Gamesa	G128-5.0MW	2013	5.0	128	PMSG	LV	2
Vestas	V164	2014	8.0	164	PMSG	–	2
Sway	Sway	2015	10.0	164	PMSG	–	0
AMSC	Sea Titan	2015	10.0	190	PMSG	MV[g]	0

[a] Permanent magnet synchronous generator (PMSG), doubly fed induction generator (DFIG) and squirrel cage induction generator (SCIG).
[b] Number of stages of the gearbox.
[c] It mounts a 3.4 MW synchronized generator in each of the two drive shafts of the main gearbox.
[d] Hydraulic system with Artemis digital displacement ® wind transmission.
[e] Two-bladed wind turbine.
[f] It includes the converter PCS 6000 Wind converter manufactured by ABB (see Section 2.2).
[g] Medium voltage PMSG based in high temperature superconductors.

a quarter of them on PMSGs with simplified gearboxes and about another quarter on DFIGs.

In relation to DFIG based turbines, their main advantages are low investment costs and high reliability [9–12]. The economic interest comes from the reduced power of the electronic converter, usually dimensioned to about 30% of generator rated power. The intended increase in reliability comes from the experience gained onshore during the last few decades. Its drawbacks are the rigorous and costly maintenance that slip rings and three-stage gearbox demand, the limited rate of wind speed control and the necessity of a strong grid to connect with when starting operation. Moreover, turbines based on DFIG schemes can contribute to the short-circuit current during a fault because the stators are directly coupled to the grid, hindering the compliance with fault ride-through grid codes.

The DFIG scheme has been adopted by Repower, Sinovel, Guodian, 2B-Energy and by Bard in the Bard 5.0 offshore wind turbine. It also should be noted that all the DFIGs set up in these WECSs seem to have a low voltage output, although technical details are not always disclosed.

In relation to PMSG based turbines, the type of generator reduces operation and maintenance (OM) costs, due to its lack of slip rings, and simplifies or eliminates the gearbox, due to its reduced rotating speed. DD configurations with PMSGs are also attractive because of the gearbox elimination and cost reduction because of its small pole-pitch design. Full-scale converters in these WECSs optimize the energy capture over a greater range of wind speeds than DFIG solutions, reduce mechanical loads over the drive-train and make it easier to fulfil fault ride-through requirements. Its main drawback is the higher cost of the electric generator.

The PMSG with simplified gearboxes strategy has been adopted by Areva, Dewind, Gamesa, Vestas and by Bard in the Bard 6.5 turbine. The M5000 incorporates a medium voltage (MV) generator, whereas the G128-5.0MW and the Bard 6.5 incorporate low voltage (LV) generators. In the Bard 6.5 turbine, the company has shifted from a DFIG scheme to a PMSG based WECS. It is also remarkable that its gearbox is equipped with two drive shafts, each of them coupled to a 3.4 MW generator.

DD approaches with PMSGs are the clear trend in the 6.0–10.0 MW range. This strategy has been adopted by Siemens, GE Energy, Hyundai, Mitsubishi, Alstom, Nordex, Mingyang, Sway and AMSC. Regarding the output voltage of these PMSGs, the SWT-6.0-120 manufactured by Siemens has LV output, whereas the HQ5500 and the N150/6000 in development by AMSC-Hyundai and Nordex, respectively, have MV output. Specially innovative is the SeaAngel, in development by Mitsubishi PSE, mainly due to its hydraulic transmission system. This transmission has two hydraulic motor drives, each of them connected to a MV half-rated PMSG. The control over the torque-speed of those shafts that the hydraulic system is intended to provide makes the full-rated electronic power conversion unnecessary.

Finally, it is worth noting that although 75% of the OWTs fully connected to the grid during last year were SCIG based turbines [13,14], only SWT 4.0-130 in Table 1 follows this strategy. In the SWT-6.0-120 the manufacturer has shifted to PMSG. This decision could be because of two related issues. On the one hand, bearing in mind that the capital costs of OWTs shares about 30% of the overall costs of an offshore wind project [3], the influence of setting up a bigger turbine in terms of cost is low. Therefore, the offshore sector is focusing on increasing output without increasing logistics [15]. In this context, the difference in price between a PMSG and a SCIG with similar characteristics is negligible. On the other hand, the significant reduction in OPEX that DD configurations are expected to lead to is only possible with PMSGs.

2.2. Power converters in WECSs

Power converters are having a key role in the integration of renewable energy sources of electricity (RESE) in electric power systems [11]. When installed in new multi-MW turbines most of their contributions are closely related to control issues. For example, they enable the control of the generator in a variable-speed mode coordinating it with mechanical pitch control, maximizing the power extraction from the wind and softening the mechanical solicitations over the drive train [12].

Moreover, if they are full-power rated they decouple the generator from the grid and, therefore, they allow the use of generators with fewer maintenance requirements and control active and reactive power independently at the turbine level. A proper control of the converter can also reduce speed and torsional oscillations that appear when the generator is directly connected to the wind turbine without any assistant damping device. From the point of view of the power flow, torque oscillations in the generator shaft are reflected in the DC-link of the back-to-back converter. A damping strategy for speed-torque oscillations of the generator through a compensation of the DC-link current is proposed in [16].

An interesting topology for LV full-rated power converters in the power range between 1 and 6 MVA is described in [17,18]. The converter system has a modular design, with up to a six parallel 4-quadrant full-power converters and is electrically connected to the LV/MV transformer in the nacelle [17]. Each converter module is a conventional 690 V two-level back-to-back VSC mounting 1700 V IGBTs, and incorporates its own circuit breaker, chokes, filter, measuring system and control unit. This scheme with a variable number of active modules is incorporated by Gamesa in the G128-5.0MW turbine. Apart from the increase in availability, this approach reduces the power losses significantly when compared with converters which modules are always active (Fig. 2).

Other manufacturers also offer off-the-shelf LV full-rated power converters for WECSs in their portfolio. The ACS-800 family manufactured by ABB has an optional parallel connected sub-converter configuration. It has a modular design with IGBT power modules with integrated DC capacitors, air or liquid cooled, making it possible to use the same converters for DFIGs, SCIGs or PMSGs [19] . The G3 converters manufactured by Ingeteam follow a similar six-module pattern for full-rated power converters between 2 and 10 MVA [20] . The MV3000 family manufactured by GE Power Conversion, formerly known as Converteam, is another option available [21]. For DFIGs, in most cases, the converters have the same characteristics as those used in full-rated power converters but with fewer modules.[3]

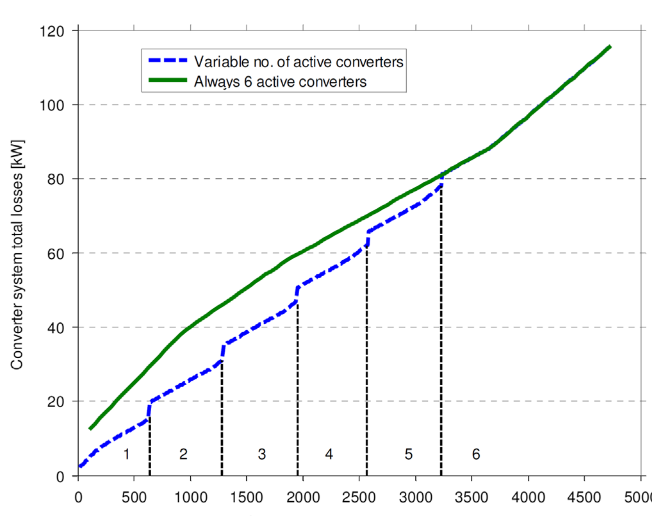

Fig. 2. Power losses in the G10X 4.5 MW converter [18].

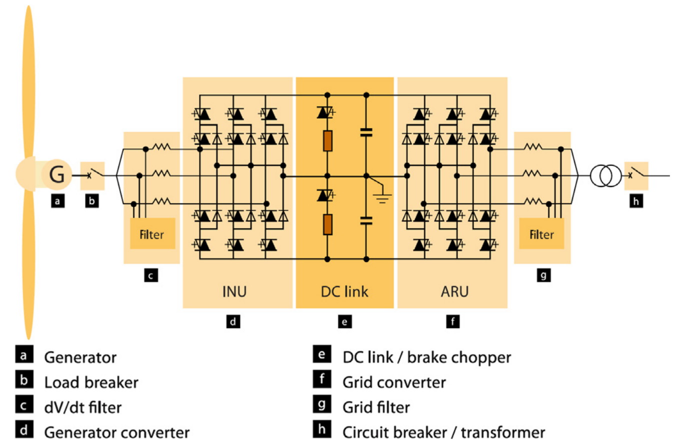

Fig. 3. PSC 6000 MV converter topology (ABB) [22].

For oncoming OWTs of rated power near and above 10 MW, manufacturers are suggesting MV converters as a better approach, most of them offering off-the-shelf MV three level neutral point clamped (NPC) converters with IGCTs, press-pack IGBTs or HV-IGBTs (Fig. 3). Some manufacturers suggest that as the power rating of wind turbines increases, MV converters become more competitive in terms of space, weight, number of components and reliability [22]. This supposed higher reliability comes from a smaller number of semiconductor devices and from the fact that these converters are based on well establishedtechnology for MV industrial drives. However, it should be taken into accountthat a failure on a semiconductor device in such a converter could stop the production of the OWT completely, whereas a similar failure in a converter with a modular approach as that described in [17,18] would have only a partial effect on the production of that OWT. The improvement in reliability those converters are supposed to offer should be analysed in detail. Other MV converters with similar characteristics can be found in the Ingeteam and GE portfolios.

2.3. Long-term proposals

The first fixed-speed wind turbines (*Danish* concept) were based on SCIGs with the electrical generators directly connected to the grid via transformers. Their rotating speed was almost constant, due to the small slip variations, and it was slightly above the synchronous speed. These types of turbines are not expected to have much application in the future, neither onshore nor offshore, apart from those turbines already operating in a number of wind farms worldwide.

However, in current research on electric topologies for OWPPs, *fixed-speed* WECSs are understood to be turbines with no electronic converter and indirectly coupled to a VSC converter that collects the power generated by all the turbines forming a cluster. The converter performs a common speed control for all the turbines regulating the frequency in the CS. Recent papers focused on these proposals are commented on in Section 3.2.

Regarding OWTs with their output in DC, several configurations have been proposed by the research community in recent years

[3] The modularity in the design and manufacturing of a converter should not be confused with the variable number of active modules strategy, although the latter also has a modular design.

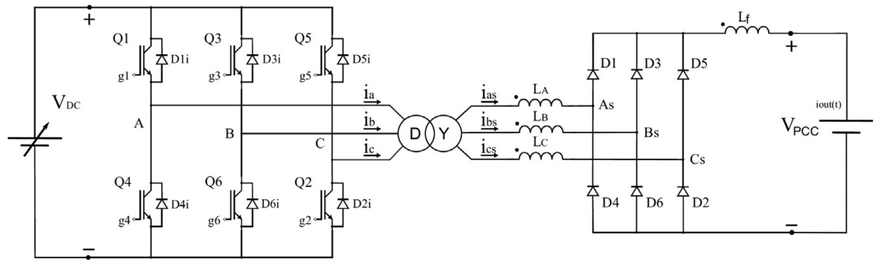

Fig. 4. Alternative DC/DC output power stage for OWTs [26].

[1,23–26] . In ageneral sense, their main objective is to enable pure DC windfarm layouts. By doing so, a reduction of the losses in the CS could be achieved, as well as a direct tapping of these OWTs to a VSC-HVDC transmission system.

Most of the proposals for WECSs with DC output have considered a PMSG followed by a rectifier and a DC/DC transformer. Proposals include either passive or active rectifiers. Passive rectifiers are based on diode bridges with no control capability, whereas active rectifiers are based on full bridge VSCs based on IGBTs. These active converters provide full control capability of the active and reactive power obtained from the generator.

In [24–26] an output power conversion stage for DC wind turbines is analysed (Fig. 4). Although this power stage is simple and familiar [23,27,28], when the properties of the transformer and the control of the VSC-HVDC system are considered, some interesting features arise:

- The control of the output stage is very simple. Variable frequency three-phasesix-pulse control can be used with minor modifications.
- The only power semiconductors in the MV side are diodes and, therefore,there is no need for control circuits there. The system can be built with low cost existing fast diodes up to levels of 33 kV.
- SiC diodes could lead to a significant increase in the output voltage, although their cost may be too high until mass production is achieved.
- Nano-crystalline cores could be used to decrease the losses in the medium frequency power transformer.

3. Collector systems (CSs)

The limits of the CS are the medium voltage gas insulated switchgear (GIS) placed inside turbine tower bases and on the OS. Its purpose is to gather the electric power production of all the turbines and bring it to a central collection point (CCP), which then ties in to the main grid through the TS. This section presents state of the art MVAC collector systems (Section 3.1) and proposals of multi-terminal VSC based collector systems (Section 3.2) and MVDC collector systems (Section 3.3).

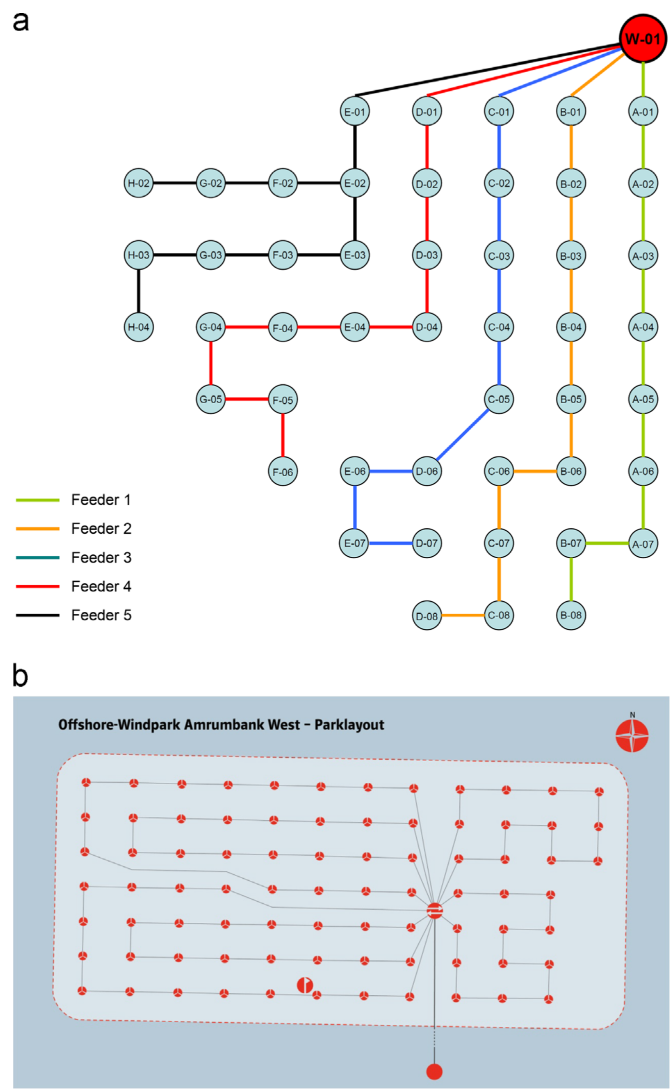

Fig. 5. MVAC collector system designs in commissioned OWFs. (a) Radial and dendrite feeders at Lillgrund (Vattenfall 2007) and (b) double sided ring CS at Amrumbank (E.On 2015).

3.1. Typical MVAC collector systems

There are a number of possible turbine arrangements in wind farm MVAC collector systems [29–31] but three of them are being currently considered, *i.e.*, radial, dendrite shaped and double-sided ring collector systems.

A *radial CS*, also known as string CS, is that in which a number of OWTs are connected to a single cable feeder within a string (feeders 1–4 in Fig. 5(a)). The number of wind turbines on each string feeder is determined by the capacity of the generators and the maximum rating of the MVAC submarine cable within the string. Its advantages are the simplicity of its control and the smaller total cable length. Its major drawback is its poor reliability, as cable or switchgear faults at the hub end of the string can prevent all downstream turbines from exporting power. This design has been chosen, for example, in Barrow, Lillgrund, Thorntonbank-1 and Belwind-1 OWFs.

In a *dendrite shaped CS* the turbine to be connected to the OS is placed in the middle of the cluster (feeder 5 in Fig. 5(a)). In addition to an improved availability, the cable that interconnects the turbines can have a lower current rating than in the radial design. Applications of this dendrite shaped CS can be found in a

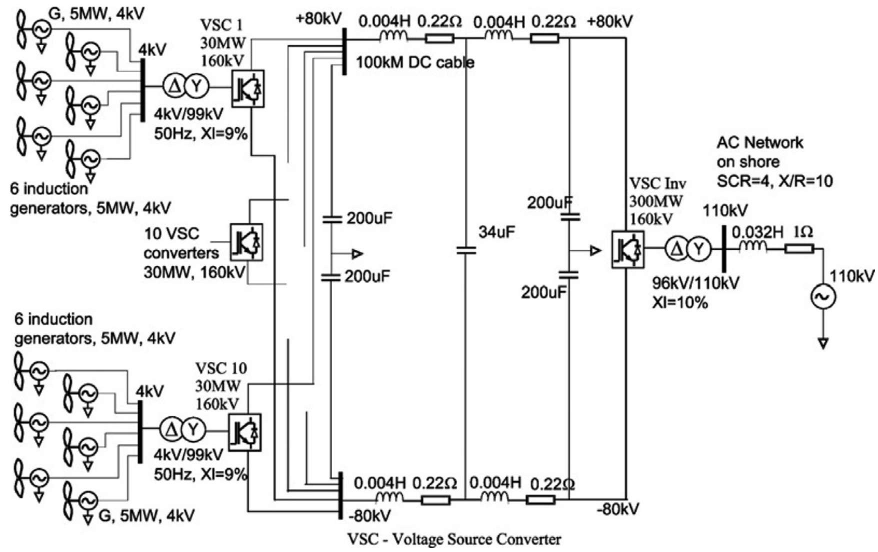

Fig. 6. 300 MW OWPP with centralized power conversion and parallel VSC-HVDC connection [35].

number of commissioned OWFs, *e.g.*, Horns Rev, Kentish Flats, Egmond aan Zee, Horns Rev 2, Lillgrund, Thanet and Walney.

In a *double-sided ring CS* the security of supply is improved interconnecting the last OWTs in adjacent strings (Fig. 5(b)). Therefore, cable stretches close to the hub end of the clusters need to be sized for the power output of double the number of OWTa. Redundant schemes have been used, for example, in commissioned North Hoyle, Greater Gabbard and Thorntonbank II and in OWPP under construction such as Amrumbank.

The voltage in these CSs has been 33 kV in all OWFs operating and under construction. However, the continuous increase in turbine size and new dry-type transformers up to 72.5 kV [32] suggest to consider 45 kV or 66 kV in the optioneering phase of OWPP projects.

3.2. Multi-terminal VSC based MVAC collector systems

Multi-terminal HVDC schemes based on VSC converters have been suggested with different purposes in the context of OWPP - electric topology research. In [33,34] , for example, a four terminal HVDC topology is proposed to take the power generated by three OWFs to the onshore grid through a converter placed onshore. These systems are known as *multi-terminal VSC-HVDC transmission systems* and they will be commented on in Section 4.3. However, multi-terminal VSC-HVDC schemes can also be understood in a different sense.

Several authors have proposed topologies in which turbines are clustered around VSC converters sharing common voltage and frequency control. In [1] it was already suggested that the possibility of having an independent local MVAC collector system in which both the voltage and the frequency are fully controllable with the converter placed at the OS. More recent studies propose CSs where the turbines interconnected in each cluster share the same speed control provided by a power converter by means of CS frequency control [35–39].The main advantages of these schemes are, in some cases, the possibility of using low cost *fixed-speed* WECSs with no power converter, and in other cases the avoidance of the OS.

In [35] a new topology for a 300 MW OWPP based on a parallel multi-terminal VSC-HVDC link is proposed (Fig. 6). The OWPP - consists of 60 squirrel-cage 5 MW generators connected to a common DC bus using 10 VSC converters. Each cluster comprises six generators and asingle 4/99 kV transformer operating at the variable frequency established by the 30 MW and 160 kV VSC dedicated to the cluster. In [36], the same author proposes a serial arrangement of converters working as current source inverters (CSIs) as an alternative multi-terminal scheme. By doing so, it is theoretically possible to avoid the installation of power transformers in OSs, which could lead to asignificant decrease in their capital costs. However, an increase in the cost of CSIs based on self-commutated switches should be considered, when compared to VSCs. This cost increase would be related to some practical issues as series connected switches, terminal capacitors and three-level control and insulation.

Both serial and parallel proposals are quite similar in relation to the MVAC collector system. Their differences arise in the design of the converter and the DC switch bay placed at the OS. As it has been mentioned before, the main advantage of these proposals is that they allow the use of simpler WECSs as astrategy to decrease the capital costs of an offshore wind project. However, itmakes sense to consider two issues related to the feasibility of these proposals, *i.e.*, the power lost due to a non-optimum speed control of the WECSs and the actual cost saving potential of these schemes.

Regarding the decrease in the power production of the turbines in a cluster due to the common speed control, some studies suggest that the inability to operate individual machines at the most optimum speeds should not cause a great loss in efficiency. That assumption is presented in [35,36], where authors assume that the wind profile will be largely similar for a group of closely located turbines. On the contrary, the simulations reported in [37] show that the turbines controlled by an unique VSC converter can obtain about 92% of the power obtained when each OWT has independent speed control.[4]

The same issue is analysed in [38,39]. These studies present the difference between the power production of clusters of turbines with individual and collective speed control as a function of the number of turbines in acluster and of the standard deviation of the wind speed within the wind farm. The result presented in [38] for a cluster of 10 turbines and a deviation of 1 m/s within the OWPP is about 98%. These results seem to support the assumption presented in [35,36], but we should bear in mind that the loss of 2% of the potential production of a big OWPP is an issue.

[4] The mean wind speeds chosen for the four WECSs considered in this analysis are too divergent to be taken as realistic. The authors probably try to analyse a worst case scenario.

Regarding the cost saving potential of these proposals, some quick numbers can be useful. The capital cost share of the electronic power converter in a typical 5 MW£6 million offshore turbine is about 6% [40]. And the capital cost of OWTs account for about 28.3% of the life-cycle costs of a typical baseline OWF [3]. Therefore, the cost saving potential of using WECSs with no power electronic converters can be somewhere near 1.5% of the life-cycle costs of an offshore wind project. In fact, that margin would be probably even smaller owing to an increase in the capital cost of the OS and of the WECSs. The former due to the modular design of the converter and the latter due to an increase in the solicitations over the mechanical structure of the OWT.

Finally, a short comment on the frequency of the CS. The basic idea in the topology proposed in [41] is to minimize the losses by designing asingle-phase medium-frequency CS. The frequency in the proposed CS is different to the industrial standard of 50/60 Hz, which is possible if power converters decouple it from both the generators and the onshore main grid.

3.3. MVDC collector systems

Conceptually, MVDC collector systems are those linking turbines with DC output and a HVDC transmission link to shore. In a general sense, the arrangement ofthese CSs can be one of those previously commented on for MVAC collectorsystems. In [42], for example, radial or star configurations are considered while analyzing the transient performance of DC protection systems.

However, there are some considerations specific to MVDC collector systems:

- Number of DC/DC transformation steps.
- Series connection of turbines avoiding/simplifying the offshore substation.
- Availability of DC breakers and protection systems, and resonances insidemeshed DC grids.

In relation to the number of required DC/DC transformation steps, it is assumed that only one is required if the DC voltage from the OWTs is high enough(20–40 kV), but two steps could be required if the output voltage of the OWTs is lower [1]. The number of transformation steps is also investigated in [23]. The selected DC/DC converter is the single active bridge, with 5 MW generators, a line-to-line voltage of 5 kV and a 160 kV HVDC transmission link to the shore. Fig. 7 shows the alternatives considered in the comparison.

The cluster step-up solution (Fig. 7(a)) leads to the lowest losses because of the short distances within the windfarm. The cable losses at the distribution level are not so important and the advantages of lower losses in the cables for the two step-up configuration (Fig. 7(b)) are eliminated by the losses of an additional DC/DC converter. The overall losses in the turbine step-up solution (Fig. 7(c)) are also higher than for the cluster step-up, due to the high output voltage needed at lower power levels and to the reduced efficiency of 5 MW transformers compared to larger components [23].

In relation to the series arrangement of OWTs with DC outputs its main advantage is the possibility of avoiding the huge cost of OSs [1]. However, the cost of OSs seems to have been already assumed in OWPP projects. This does not mean that the reduction in the investment cost of OSs is not an objective, but the *series DC windfarm* seems to lose some of its interest. Moreover, some technical issues related to the serial connection of hard-switched converters such as CSIs have caused a move in the research interest to parallel connected VSC schemes [35,36]. Some of these technological challenges are special demands to balance series connected switches, very high insulation requirements for the converters placed in the nacelles, overvoltages following a short circuit in an OWT and reliability issues for the series DC windfarm as a whole [12,35].

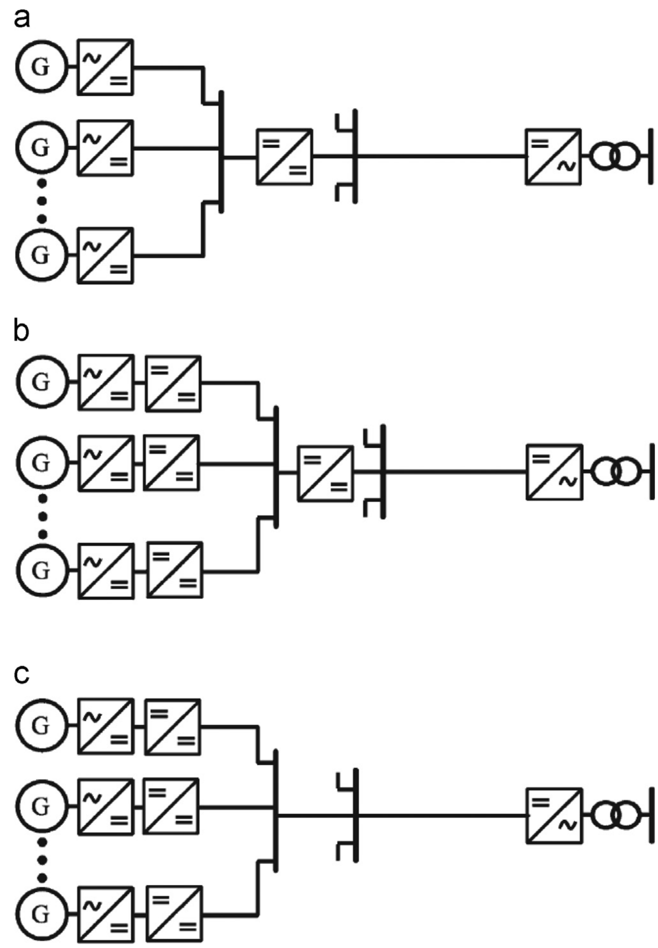

Fig. 7. Configurations for the DC grid of an OWPP [23]. (a) Cluster step-up, (b) two step-ups and (c) turbine step-up.

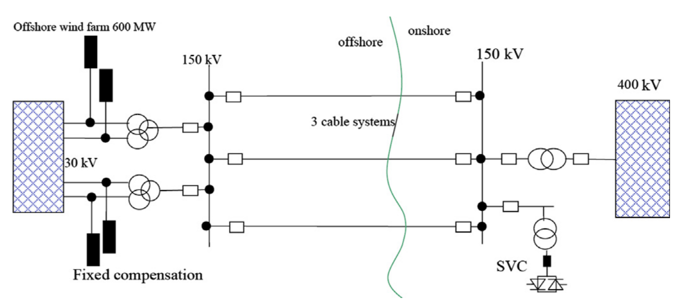

Fig. 8. Typical HVAC transmission system for an OWPP [43].

4. Transmission systems (TSs)

Most of the commissioned OWFs are using HVAC transmission systems at voltages between 110 and 150 kV (Section 4.1), and a number of OWPPs under construction or in the planning stage are considering HVDC point-to-point links to take the electric power onshore (Section 4.2). Multi-terminal HVDC systems will surely be installed in the near future, and a good number of researchers worldwide are focusing on the subject. Their application to OWPPs in conjunction with bulk power interchange corridors between countries is also under consideration (Section 4.3).

4.1. Point-to-point HVAC transmission systems

Current HVAC transmission systems for OWPPs usually include one or two OSs, cross linked polyethylene (XLPE) three-core submarine cables, onshore underground cables or/and overhead lines and the CPS. Both substations include power transformers, gas or air insulated switchgear and reactive power compensation equipment.

A key issue in these TSs is how to provide appropriate voltage and frequency control through reactive power compensation. During the last decade, a typical solution included fixed compensation offshore (usually less space demanding) and static VAr compensators (SVCs) at the onshore substation responsible of maintaining the voltage in the offshore grid within prescribed limits controlling the voltage at the onshore end of the cable (Fig. 8 [43]). During the last years static synchronous compensator (STATCOMs) have replaced SVCs, and in some cases shunt reactors at the OS have been made unnecessary by means of an appropriate P-Q control at the turbine level [44].

As regards the cables, three-core XLPE cables are the standard for HVAC transmission systems as well as for MVAC collector systems. ABB, Nexans, Prysmian and Silec (General Cable) offer MVAC inter-array and HVAC transmission solutions of this type. From the electrical side, rating pinch points (hot spots) are likely where the cable transitions from the water into air or land, with critical locations where HVAC cables come ashore and where MVAC cables raise the j-tube onto the platform [45]. From the mechanicalside, it is essential trying to avoid uncovered stretches of cable, specially under the influence of strong changing undercurrents. Most of the cable faults have their origin in failures caused by the fatigue of the armatures in these situations.

The fulfilment of the offshore wind targets established by some European countries will demand a regular supply of cable solutions at a continuous rate above 800 km per year. The submarine cable industry is trying not to become a bottleneck for the offshore wind business [8]. However, at the moment there are some open issues, like developing proper maintenance models to solve cable breaks and loops which occur during installation, and the lack of experienced staff and specialized cable-laying vessels.

In relation to power transformers, they the largest asset at the OS other than the platform itself and they drive the overall electrical and physical layout. The use of insulations other than mineral oil in these transformers is being considered(SF_6, esters, etc.) due to the risk and impact of a major transformer failure and fire on all the components of the OS [45] . In terms of busbars and switching bays at the OS, space and weight are so relevant that GIS is being exclusively used, with current thinking favoring the single busbar design for both the MV arrays and the HV export configuration (Fig. 9 [46]).

At the moment, the main challenges to optimize AC offshore substations are maximizing the power export availability and solving the uncertainties related to the influence of the offshore physical environment on equipment performance. According to [45], different solutions are being considered to increase availability such as installing two 60–70% rated transformers instead of one or enabling ringed CS designs by additional space for bigger switchgear at OSs. However, Section 3.1 has shown that the double sided rings are being currently preferred, probably because they are less space demanding solutions.

Regarding the adaptation of equipment to the marine environment, several issues demand analysis and improvement, *e.g.*, minimizing corrosion damage, defining insite intervention requirements and establishing necessary auxiliary and ancilliary services [45]. Gathering accurate and sufficient availability data about these components in operating OWFs will be essential for future analyses.

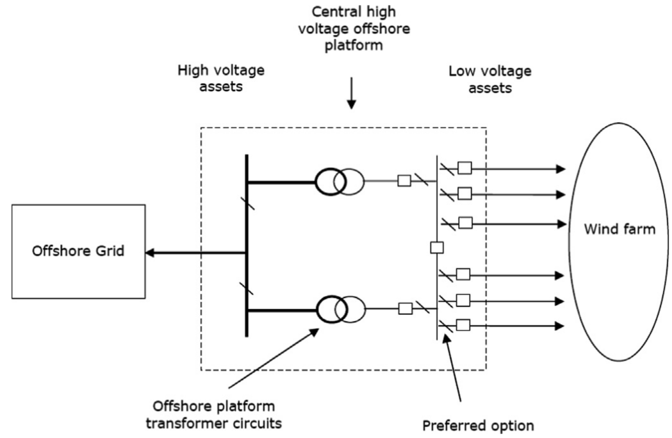

Fig. 9. Preferred AC offshore substation configuration [46].

Up to now, these OSs have been designed and constructed *ad hoc* for each OWF. However, leading manufacturers are offering already engineered solutions based on their experience, among which [47,48] are the key solutions. The former due to the experience of the company in the OSs already in operation. The latter, because of the intended adaptability of the proposed design to both HVAC and HVDC transmission systems.

4.2. Point-to-point HVDC transmission systems

The converter technologies considered during the last decade as HVDC transmission systems for offshore wind have been line commutated converters (LCCs) and voltage source converters (VSCs). However, there are several reasons not to consider LCC appropriate for OWPPs.

On the one hand, LCC converter stations have demanding space requirements that require huge and expensive OS platforms. On the other hand, VSC converter stations provide fast and independent control of active and reactive power, whereas LCC converter stations consume reactive power equivalent to about 50% of the transferred active power, making it difficult to comply with grid codes (ride-through capability) [49]. Moreover, LCC technology is susceptible to commutation failures at the inverter terminal, which would be the on-shore station. This is more pronounced in a weak AC system. The solution would be a STATCOM, to help ride through the AC system fault, to avoid repeated commutation failure. Because the LCC needs the AC voltage to be present at the rectifier and inverter at all times, black start is not possible. In such cases the off-shore station (rectifier) would require a diesel generator to generate the voltage required to start the commutation process.

During the last decade there have been several studies focused on the comparison between HVAC and HVDC transmission systems for OWPPs [30,35,49–51] . Table 2 presents a summary of the main features of both technologies when employed to connect offshore wind with the onshore main grid, considering VSC based HVDC links.

The most important component of the converter station placed at the OS is the VSC converter, which drives the design of the OS in terms of space demanded and the related cost of the supporting structure. These VSC converters are based on IGBTs, with a switching frequency usually between 1.3 and 2.0 kHz. By doing so, the content of harmonics can be significantly reduced and, consequently, the filters and converter reactors are smaller than in LCC converter stations.

A transformer connects the MVAC of the collector system to the converter in order to adapt the voltage level for conversion in the VSC device. It also provides reactance between the AC and

Table 2
HVAC *vs* VSC-HVDC point-to-point links for OWPPs.

HVAC	VSC-HVDC
Reactive current increases losses, reduces cable ampacity and demands compensation devices	There is no charging current and no limit on transmission distance beyond practical constraints
The cost and losses in substations are lower	Higher size-cost of OSs and higher losses in electronic converters
Considerable experience in project development and OWF operation	Very little experience in VSC-HVDC links for OWFs
Limited control capability on active and reactive power with STATCOMs	Independent full control of active and reactive power in both ends. Black-start capability feasible
If OWTs and the grid are synchronously coupled faults are propagated	The CS and the CPS are asynchronously coupled and faults are not propagated
Resonances between OWPP and the grid may occur	There are no resonances between cables and other AC equipment

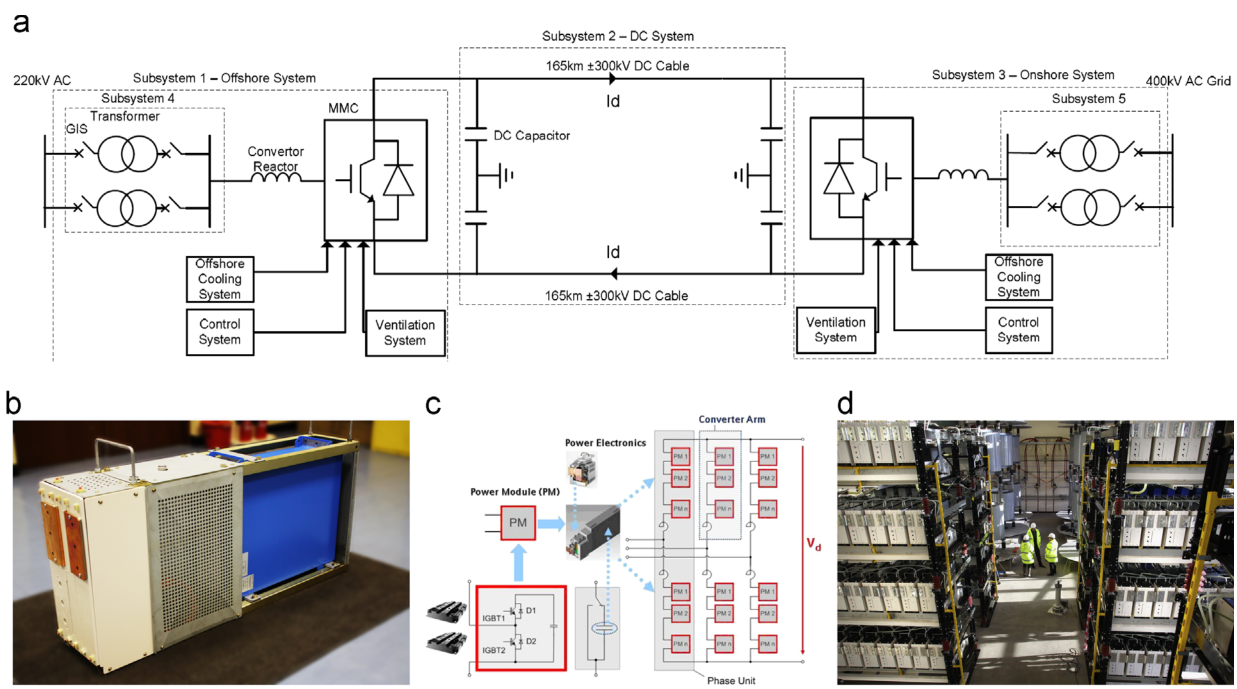

Fig. 10. VSC-HVDC point to point schemes based in MMC technology. (a) Point-to-point VSC-HVDC scheme [59], (b) converter's module (Alstom), (c) converter arm's configuration (Siemens) and (d) MMC demonstrator (Alstom).

Table 3
VSC-HVDC links under construction for OWPPs.

Project	Owner	Year[a]	Converter	Power (MW)	Voltage (kV)		Length (km)	
					AC	DC	Offshore	Onshore
BorWin1	TenneT/Mitshubishi	2012	Light	400	170/380	±150	125	75
BorWin2	TenneT/Mitshubishi	2013	Plus	800	155/300/400	±300	125	75
DolWin1	TenneT	2013	Light	800	155/380	±320	75	90
HelWin1	TenneT	2013	Plus	576	155/250	±250	85	45
SylWin1	TenneT	2014	Plus	864	155/300/380	±320	160	45
DolWin2	TenneT[b]	2015	Light	900	155/380	±320	45	90
HelWin2	TenneT[b]	2015	Plus	690	155/300/380	±320	85	45

[a] Year foreseen for the commissioning of the transmission link according to information disclosed by manufacturers [54,56], although significant delays are expected due to shortage of cable, skilled installers and cash.
[b] Mitsubishi power systems Europe has shown its interest in acquiring a 49% stake also in these links.

VSC systems and preventing zero frequency currents from flowing between the AC system and the converter [50]. A detailed description of the basic equipment that configures a VSC based OS is presented in [52], whereas detailed information about the cable systems in these TSs can be found in [53].

The main drawback of this technology during the last decade has been its loss rate near 2% per converter station. The main reason for the high losses in VSC converters was that the high switching frequency necessary to minimize the harmonic content of the synthesized wave also led to high switching losses in the valves of the converter. These VSC schemes were almost exclusively developed by ABB and were based in two level converters and three level neutral point clamped converters (ABB HVDC Light® [54]).

However, the VSC-HVDC converters currently offered by Siemens and Alstom Grid are based on multi-level modular converter (MMC) technology. The product names are the MaxSine®,developed by Alstom Grid [55], and the HVDC PLUS, developed by Siemens [56]. The increased number of voltage steps used by MMC converters reduces the harmonic content of the synthesized waveform reducing significantly, or even making unnecessary, the AC filtering shunt

reactors that previous VSC technologies demanded, although reactors in series with the converters are still needed.

The only HVDC link currently under operation based on MMC technology is the Trans Bay Cable, installed by Siemens and Prysmian between San Francisco and Pittsburgh, and commissioned in 2010. This very first experience has shown that power losses with MMC technology are around 1% per converter station [57,58] , which changes the situation of VSC technology when compared to LCC and HVAC technologies.

It makes sense to note that ABB is developing a new version of their HVDC Light for the Dolwin 2 project, that will also use a form of MMC known as cascaded two level converter [59]. Bearing all this in mind, it is reasonable to take for granted that future VSC-HVDC schemes for OWPP will employ MMC technology. Fig. 10 shows an overview of the components in VSC-HVDC point-to-point links based on MMC technology.

At the moment, there is no VSC based OS in operation for the connection of OWPPs, but there are several ongoing projects in the United Kingdom and Germany. TenneT Offshore GmbH is the offshore transmission system owner (OFTO) for the OWPPs approved and under construction in the German North Sea, and their ongoing projects to connect those windfarms with the onshore main grid through seven HVDC links are raising great expectations. The main characteristics of these projects, according to the information disclosed by manufacturers, are gathered in Table 3.

The foreseen commissioning dates of these projects should be handled carefully, according to several press news reports which point out the difficulties of keeping on schedule mainly due to shortage of cable and cash (E.ON, TenneT, Mistsubishi). Tennet submitted early last year a detailed proposal to the German Ministry for economics and technology to address, as soon as possible, several obstacles to offshore grid development [8]. There are two key aspects on the demand of the transmission system operator (TSO). On the one hand, to clarify the liability issue regarding the current cost of delays in HVDC cable lying, which could mount to hundreds of millions. On the other hand, the demand for long-term planning and advice to create a *new DC grid operator* to manage the oncoming offshore HVDC grid. However, German federal government's efforts to tackle the electricity transmission liability issues with anew law entering into force at the beginning of 2013 seem to have encountered some difficulties [6]. The situation is complicated because the draft legislation, entitled *Third law to revise energy industry regulations*, covers a number of tricky issues. These include controversial new arrangements that would require operators of conventional power stations to give advance warning of planned plant closures and creation of a system to prevent closures of plants needed to maintain electricity system stability during the period when Germany's nuclear generation is phased out and wind and solar energy begin to play an ever-larger role in electricity supply.

Finally, in relation to the rated power of HVDC converter stations under development, installing less than full OWPP capacity is being considered [60]. This is because of several factors specific to offshore projects, *i.e.*, the high cost of applying to OSs the redundancy schemes historically used in onshore substations, the variability of OWT power output due to the stochastic nature of wind, and the overloading capacity of cables and transformers which have short time overload capability based on their thermal design. On the contrary, the IGBT devices in the VSC converter have no significant overload capability, unless the converter has been specifically designed to operate below its current limit.

4.3. Multi-terminal HVDC transmission systems

To date there is little offshore electrical infrastructure installed and, so far, the tendency has been to avoid interconnection between offshore substations. However, this is not necessarily ideal from a system perspective where factors such as security of supply, availability, operational flexibility and maintenance strategies should be taken into account.

During the next few years a number of VSC-HVDC transmission links will be installed worldwide for different applications, for example, taking the electric power generated by OWPPs to shore, supplying the electricity demanded by oil and gas extraction platforms and interconnecting the electric power systems of different countries [61]. As the number of nearby operating point-to-point links increases, the possibility of enhancing availability and decreasing the overall transmission costs by interconnecting them seems reasonable.

The feasibility of multi-terminal VSC-HVDC transmission systems, also known as *DC grids*, is conditioned to the availability of appropriate HVDC breakers and associated DC protection systems. According to [62] the technology of hybrid HVDC breakers is ready, although such breakers have not been manufactured and installed in a real asset yet. According to a survey made by the CIGRÉ Working Group B4-52 among high voltage equipment manufacturers, appropriate DC circuit breakers from at least two manufacturers are expected to be commercially available in the medium-term. However, it is also becoming accepted that the cost of these DC circuit breakers will be considerably higher than comparable components in AC grids [63]. Therefore, topologies for DC grids demand careful analysis and researchers are focusing on multi-terminal VSC based HVDC schemes, as well as on their interconnection on meshed *DC grids* [64–70] .

In [69], for example, the authors suggest the following alternatives:

- *General ring topology*, in which there are lines connecting all the substations, installed offshore and onshore, in a unique ring (Fig. 11(a)). The system can be normally operated in a closed-loop. But, in the case of a fault on a DC line, the system can be operated in open-loop with no power loss if two of the lines are rated to the whole power of the system.
- *Star topology*, where each transmission line from an OS or to a CPS is connected to a central star node offshore platform, and *star with a central switching ring topology*, where the central star node of the previous topology is implemented with a central switching ring.
- *Wind farm ring topology*, in which all the OSs are connected in a ring (Fig. 11(b)). In the event of a fault in a DC line, the power generated by all the OWPPs can be managed in the offshore ring, if the lines of that ring are overrated 100%. Also, the power can be sent to the main grid if the lines connecting the OSs and CPSs are overrated 33%.
- *Onshore substation ring topology*, in which all the CPSs are connected in a ring (Fig. 11(c)). It allows more flexibility on the grid side at the cost of losing the production of an OWPP during long term failures and maintenance operations in its link.

The economics of the system is governed by the circuit lengths, the ratings of the circuits and converters, the number of necessary fast HVDC circuit breakers and isolators and the need for offshore platforms and fast communications. Therefore, selecting the optimum topology for a given application depends not only on operation and robustness requirements but also on the geographical location of the substations and wind farms and the eventual cost of HVDC circuit breakers and cables.

A comparison among the different topologies is also presented in [70] . The authors state that *wind farm ring* topology shows good performance because it can withstand different faults without losing power and using only four HVDC breakers. If shorter circuit lengths are required, the *general ring* topology can be also a good candidate but some lines need to be rated at full-power. Star topologies are considered to be non-feasible for multi-terminal

offshore connections because a fault at the central node can cause the entire system to go off line, losing the production of all OWPPs.

Finally, in [67] authors postulate that a four-terminal 1.8 GW HVDC grid based in LCC DC transformers is a better alternative to apoint-to-point HVDC. It is assumed that electronic DC transformers are capable of performing voltage stepping, voltage/power regulation and fault isolation, considering the conclusions presented in [66]. The converters proposed for the DC transmission network are both LCC and VSC, and presented conclusions are supported in detailed PSCAD/EMTDC simulations. In [68], the same authors compare the performance of LCC and VSC converters working in conjunction with DC transformers. Bearing in mind the results presented, the authors state that the proposed hybrid topology may provide means for wider access to existing HVDC transmission links.

5. Conclusion

Several new turbine prototypes in the 4.0–6.0 MW range have been unveiled during the last year, as well as a number of new turbine concepts in the 5.0–10.0 MW range. Among the WECSs in these turbines, there is a clear trend to use PMSGs and full-power converters. Direct drive solutions are the most common, although PMSG solutions with simplified gearboxes and DFIG solutions are also being considered. In this context the distrust shown by some analysts to the fact that most of the world's known rare earth material reserves are concentrated somewhere in Asia makes no sense.

Regarding the output voltage of the generator, the foreseen shift to MV has taken place in some of the turbines. However, other prototypes with rated power up to 6.0 MW continue to set up LV equipment, in some cases using double output shaft gearboxes. There is also a 7.0 MW proposal based on a hydraulic transmission which does not need an electronic power converter.

All the OWPPs operating or under construction have a MVAC - collector system. The most common design among commissioned OWPPs is the dendrite shaped variant of the string design. However, one OWPP commissioned recently has atypical string design CS, whereas three recently commissioned OWPPs have chosen double-sided ring designs in order to improve the

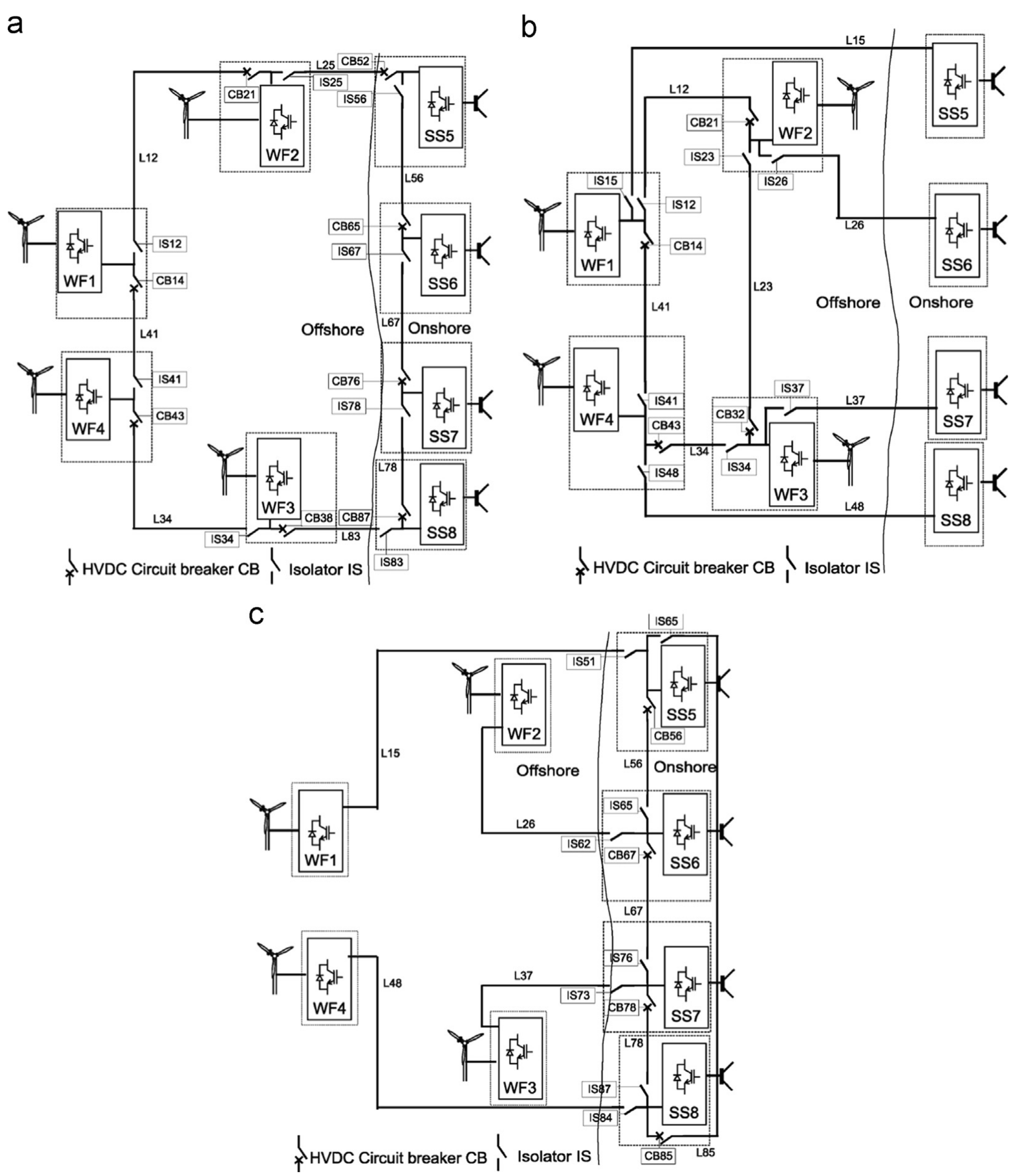

Fig. 11. Multi-terminal HVDC-VSC topologies [69]. (a) General ring, (b) wind farms ring and (c) substations ring.

reliability of the CS. Although no clear trend has been detected, double sided ring designs might be favored in the future.

Interesting long-term research is ongoing in relation to turbines with DC output and*fixed-speed* WECSs. The latter are associated with multi-terminal VSC based MVAC collector systems, in which a high-voltage medium-power converter provides a control common to all the OWTs in a cluster. These proposals can also be considered as particular design cases of the converter placed at the OS in AC/DC windfarms.

Point-to-point HVAC transmission links have been used in most of the commissioned OWFs and in most of the OWPPs currently under construction. The exceptions are the MVAC transmission systems in OWFs with no OS, and the VSC-HVDC point-to-point links under construction in Germany and the United Kingdom. The three main HVDC manufacturers offer low-losses MMC converters, although only the 400 MW and ±200 kV Trans Bay Cable project is already operational. Currently, it is accepted that the break even distance between HVAC and HVDC technologies in relation to offshore wind is somewhere between 50 and 80 km.

As the number of offshore assets increases, it seems reasonable to expect their interconnection, bearing in mind system level issues like the overall availability or the maintenance costs. And the offshore wind business is at the very heart of this trend. Therefore, different aspects of future DC grids are currently under investigation by the research community. Of special interest is the activity of several Cigré working groups within the B4 Study Committee, as one of the main forums worldwide gathering HVDC experts interested in future DC grids.

Acknowledgment

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